

A Comparative Study of the Elastic Wave Radiation from Earthquakes and Underground Explosions*

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Summary

A detailed analysis of the surface wave radiation from two underground explosions (BILBY and SHOAL) and an earthquake near Fallon, Nevada, whose epicentre is only 60 km from SHOAL, indicates that: (1) at long periods the surface wave radiation from the earthquake can be explained by a pure quadrupole (double couple) source, but at higher frequencies the radiation pattern contains asymmetries which suggest effects due to rupture propagation; these would require higher-order multipole terms in the source equivalent representation; (2) the surface waves from the explosions can be explained by superimposed monopole and quadrupole sources, with no indication of higher-order multipole terms, at least in the period range comparable to that in which the earthquake signal was recorded; (3) the principal conclusion of this study is that the anomalous radiation from the explosions is probably due to stress relaxation around the shock-generated shatter zone and not due to earthquake triggering. Comparative analysis of SHOAL and FALLON shows that: (1) the ratio of the Love wave amplitude generated by the earthquake to the Love wave amplitude from the explosion increases with period, which implies a larger source dimension for FALLON; (2) the normalized spectral ratio of Love wave amplitude to Rayleigh wave amplitude, considered as a function of period, is nearly constant and close to unity for the explosions, but larger for the earthquake by a factor of two or three, and increasing with period. These differences might be useful in distinguishing earthquakes from explosions (at least in the magnitude range of the events used in this study, m_b 4.4 and above), as well as for estimating source parameters, such as stress, which are of fundamental geophysical interest.

Introduction

The surface waves radiated by explosions and earthquakes are of special interest since they provide information about the intrinsic character of the source and the propagation medium. In this study we consider the following questions: first, what are the differences between the long-period radiation from earthquakes and explosions, as determined from the surface wave spectra? Second, what are the spatial radiation patterns from these two types of sources, and how do they differ?

These questions are related to the problem of discrimination between the source types, and hence are comparative in nature. In addition to considering these

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questions, we also attempt here to provide a quantitative description of the properties of the individual sources.

Since our primary intention is to compare the radiation from earthquakes and from explosions, it is desirable to have at least one earthquake-explosion pair with a common origin point and common recording stations, so that the effects of propagation can be minimized. Ideally these sources should also be matched in radiated energy, so that a simple direct comparison can be made without the necessity for corrections which are complicated and perhaps not completely understood. These conditions of course are impossible in practice; the closest we could come to meeting them was to use records from the Long Range Seismic Measurement (LRSM) station network, which has well-calibrated sensitive instruments and provides good azimuthal and distance coverage from the Nevada Test Site; we also chose an earthquake matching one of the explosions as closely as possible in location and magnitude; an appropriate event pair for this purpose is the SHOAL explosion and the earthquake of 1962 July 20 near Fallon, Nevada. The parameters of all the events used in this study are given in Table 1. It is seen that the desirable criteria described above are reasonably well fulfilled.

Since we are interested in the nature of the explosion source, we also consider the BILBY explosion, which was well recorded and of reasonably large magnitude. We compare this explosion with SHOAL in order to verify that the observed properties of the radiation from SHOAL are typical of other explosion events, and also to judge the variation of these properties with changing yield and source medium.

Fig. 1 shows the location of the sources and the stations. It is evident that many of the receivers have a common propagation path for the SHOAL and FALLON events. Fig. 2 shows the response of the long-period instruments at the LRSM stations. The frequency range in which the signal-to-noise ratios required for this research were deemed adequate is indicated by the horizontal bar; all spectral data were corrected for instrument response within this range, and data outside this range were rejected.

Unfortunately the azimuthal coverage of stations toward the west of the sources is rather sparse, and therefore some of our fits to the azimuthal dependence of the data must be regarded as tentative. Nevertheless, a large amount of data is available which is in reasonably good general agreement with our theoretical predictions.

Part of the theoretical framework for this study is based on the work of Archambeau (1968, 1972) which is also discussed by Lambert, Flinn & Archambeau (1972). Briefly, this theory provides a description of tectonic effects in terms of an initial value formulation, taking into account the initial stress field and its relaxation during the rupture process. A discussion of the theory is given in detail by Archambeau (1972). The present application of this theory is two-fold: first, as a means of guiding

Table 1

Description of data samples used

Name	Date	m_b	Medium	Location	Origin time (GMT)	Epicentral co-ordinates
BILBY	1963 13 Sept.	5.8	Tuff	Nevada Test Site	17 00 00.1	37 08 38 N 116 01 18 W
SHOAL	1963 26 Oct.	4.9	Granite	Sand Springs Ranges, Nev.	17 00 00.1	39 12 01 N 118 22 49 W
FALLON	1962 20 July	4.4	$h = 15$ km	Churchill City, Nevada	09 02 08.3	39 39 N 118 13 W

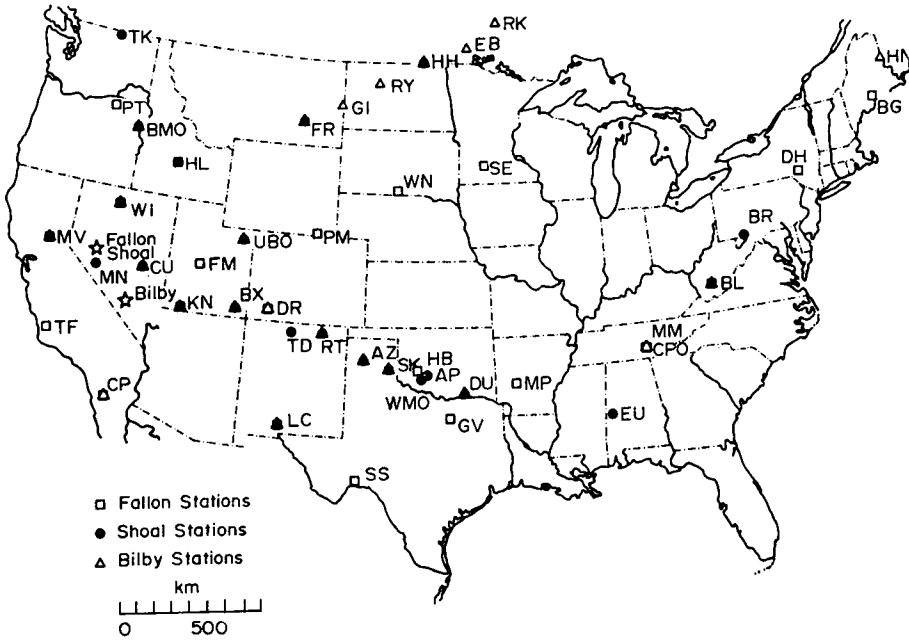


FIG. 1. Distribution of stations used in the analysis of the SHOAL, FALLON and BILBY events.

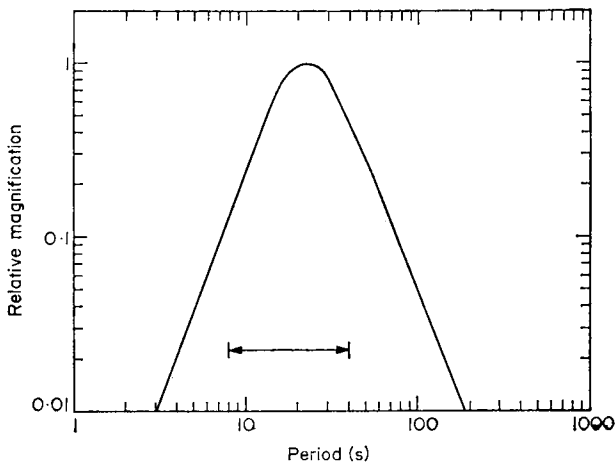


FIG. 2. Long-period LRSM seismometer amplitude response. The indicated period range, 8–40 s, is the band within which good signal power was observed for the events studied.

the development and in interpreting the observations from the earthquake source; second, as a framework for interpretation of the anomalous radiation from explosive sources, which we assume to be of tectonic origin.

Relative excitation of surface waves

Signal analysis

To study the surface wave radiation we used a digital computer program which measures both the amplitude spectrum and the dispersion of the surface waves. This program, based on routines originally written by Alexander (1963), is described in detail by Archambeau & Flinn (1965). The program automatically performs a sequence of operations, ultimately giving the signal group velocity and amplitude spectrum corrected for instrument response and group delay. The amplitude spectrum is compared to a sample of noise preceding or following the signal, and the program flags and deletes from further analysis the period ranges in which the signal-to-noise ratio is too small to allow meaningful interpretation of the signal spectrum. The group velocity is calculated using a comb of narrow-band recursive digital filters (Archambeau & Flinn 1965). At each of many closely-spaced frequencies the signal waveform is put through a narrow-band phaseless digital filter ($Q = 500$ in this study; for background see also Rader & Gold 1969). The envelope of the filter

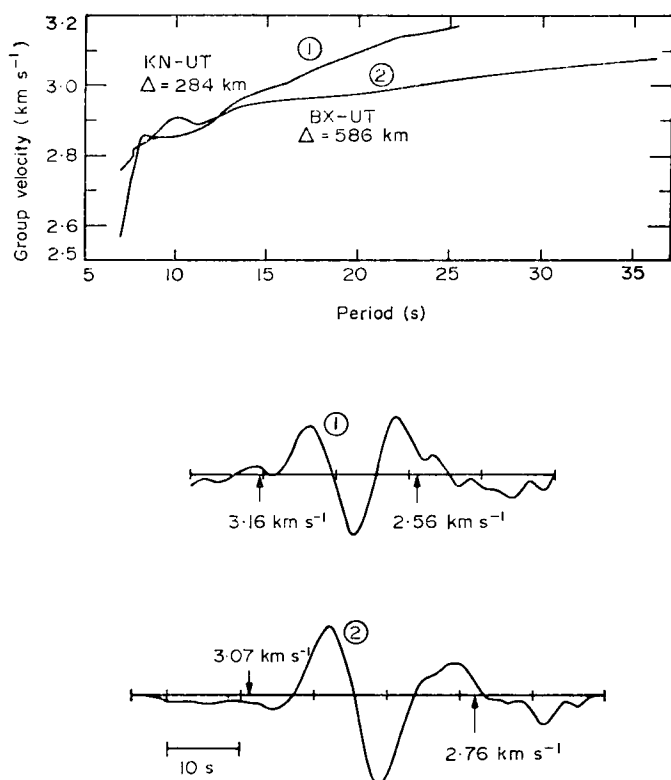


FIG. 3. Examples of surface wave signals and the associated group velocity dispersion obtained from these signals using narrow-band filtering methods.

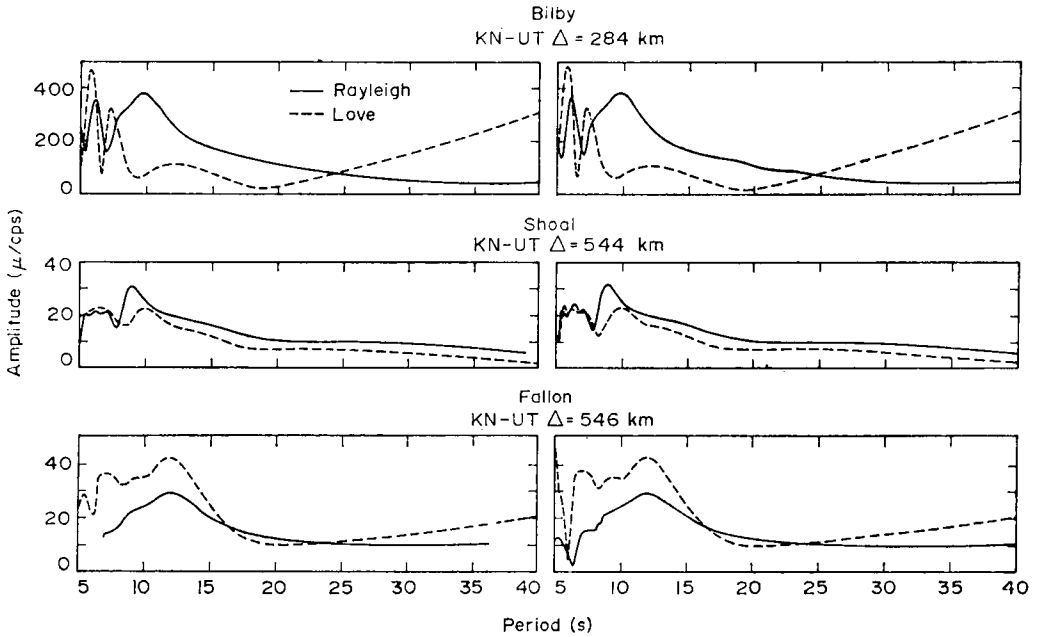


FIG. 4. Examples of surface wave spectra from the three events studied. The signal sample and the group velocity for the BILBY Rayleigh spectra are shown in Fig. 3. Fourier spectra of the signals are shown on the left and the group spectra obtained by narrow-band filtering on the right.

output at each frequency is calculated and the time of occurrence of the largest maximum in the envelope is picked. This maximum occurs at the group arrival time (i.e. the energy arrival time) of the dominant mode present at that frequency. The epicentral distance divided by this time is thus the apparent group velocity of the dominant mode, at the centre frequency of the filter. Group velocities of secondary envelope maxima are also detected and displayed.

The frequency variation of the amplitude at the times of occurrence of the dominant mode arrival gives an estimate of the amplitude spectrum of the dominant mode, and this therefore provides a method for determining surface wave mode spectra as a function of frequency. We call such spectra *group spectra*. These can be determined for each mode present at a given frequency. Fig. 3 shows examples of raw data and the group velocity curves determined by the program. Fig. 4 shows a comparison between the ordinary Fourier amplitude spectra and the group spectra. In general we have found that these two types of estimates agree to within a few per cent in the frequency range in which the signal-to-noise ratio is greater than about 1.5, even when more than one mode is present. We believe the group spectrum to be intrinsically more reliable than the Fourier spectrum, since we can associate a group arrival time with each spectral estimate and thus eliminate those points in the spectrum which are badly contaminated by noise. We have therefore used the group spectral estimates consistently in the present study.

Spectral comparisons

Fig. 5 shows observed surface wave spectra from BILBY as a function of distance along a line of stations at roughly the same azimuth from the source. In the next section we discuss the radiation patterns for BILBY and show that stations along this

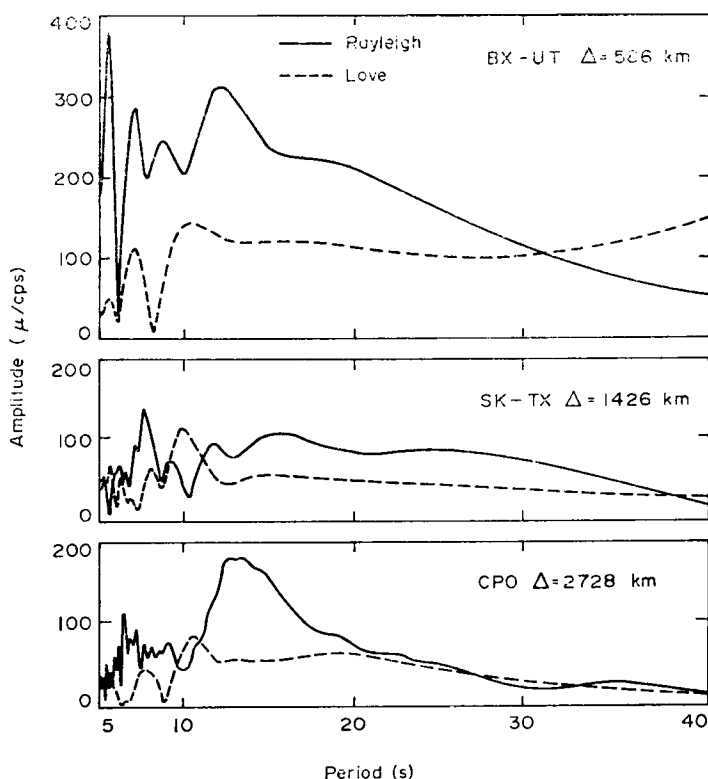


FIG. 5. Surface wave spectra at three distances for the BILBY explosion. The stations are at approximately the same azimuth from the source. Note that the Rayleigh wave excitation is generally higher than the Love wave excitation.

particular azimuthal sector lie near the maximums of the quadrupole lobes for both Love and Rayleigh waves. However, these spectra show that the Rayleigh wave excitation is generally greater than the Love wave excitation over the range of observations, 5- to 40-s period, and that the observed spectra peak near 10-s period. The exception to these generalizations is the Love wave spectrum at BX-UT, which shows an increase in amplitude in the 30- to 40-s period range. Since the time sample used to obtain the spectral estimate at this near distance range was short (the signal there being quite pulse-like), corrections for sample trend and the like are more uncertain, and we feel that this feature in the spectrum may be an artifact of our procedure.

The BILBY spectra can be usefully compared with the FALLON earthquake spectra shown in Fig. 6. We see that for FALLON the Love wave spectra generally have greater power than the Rayleigh wave spectra at all distances (which is opposite to the relation for the explosion) and that the spectral peak is near 20 s, although the Rayleigh wave spectrum does not have a clearly defined absolute maximum. In any case, even a casual comparison of the spectral characteristics of the surface wave spectra from the two sources shows that the Love wave excitation from the earthquake is relatively much greater than from the explosion, and that the spectral excitation is shifted toward longer periods. Much of the detailed character of the spectra is of course controlled by the structure but the spectral characteristics of the sources appear to cause the changes in these gross properties.

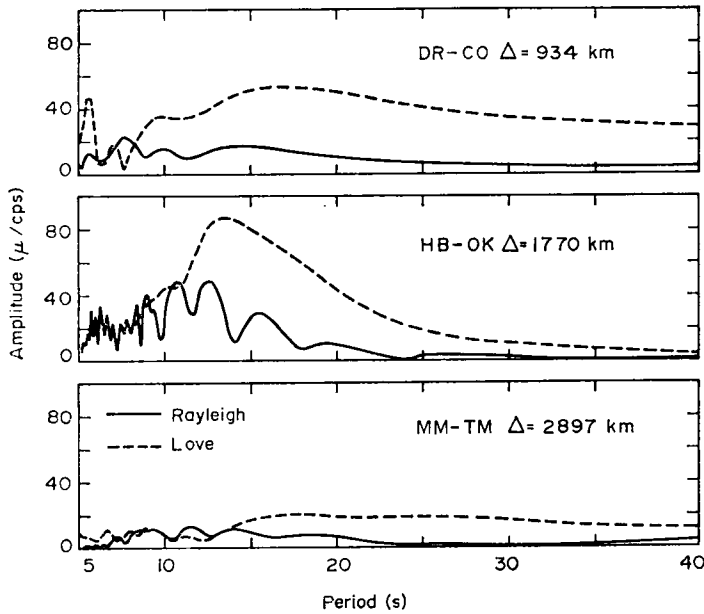


FIG. 6. Surface wave spectra at three distances for FALLON. The points of observation are at approximately the same azimuth from the source. Note that the Love wave excitation is generally greater than the Rayleigh wave excitation.

Fig. 7 shows comparable spectra for the SHOAL event. In general the spectral amplitudes are rather small and therefore noise is a significant background effect. We regard the rise in the spectra beginning around 30 s and extending to the 40-s limit to be spurious and to be due either to imperfect knowledge of the instrument response at long periods, or to ambient seismic noise, or both. Ignoring this suspect part of the spectrum, we note that the spectra of both types of surface waves peak near 10 s. The Rayleigh wave amplitudes in this restricted period range are usually about the same as or greater than the Love wave amplitudes. The explosion indeed produces surface waves with relatively greater excitation at short periods than the comparable earthquake, but does not generate Love waves with anything approaching the same efficiency as a comparable earthquake. Another means of comparing the frequency dependence of the Love wave excitation from an earthquake and an explosion is to investigate the ratio of the normalized Love wave spectra. Fig. 8 shows the Love wave spectra for SHOAL and FALLON recorded over nearly identical paths. The spectral ratio for the Love waves should be essentially independent of path and should show source differences directly. Furthermore, the Love wave excitation is a very slowly varying function of depth, which for this source depth difference of around 20 km should be only a small effect (Harkrider 1964); hence we expect to see principally the spectral differences in the source equivalents themselves. The ratios of Love wave spectra, shown in Fig. 8, substantiate the relatively greater excitation of short-period Love waves for an explosion relative to an earthquake of comparable body wave magnitude. In terms of a relaxational source this could be explained in terms of a much larger source dimension for the earthquake than for the tectonic source associated with the explosion; this is consistent with the hypothesis of stress relaxation from the region around the shock-induced shatter zone. We will show that where the power is high in both terms of

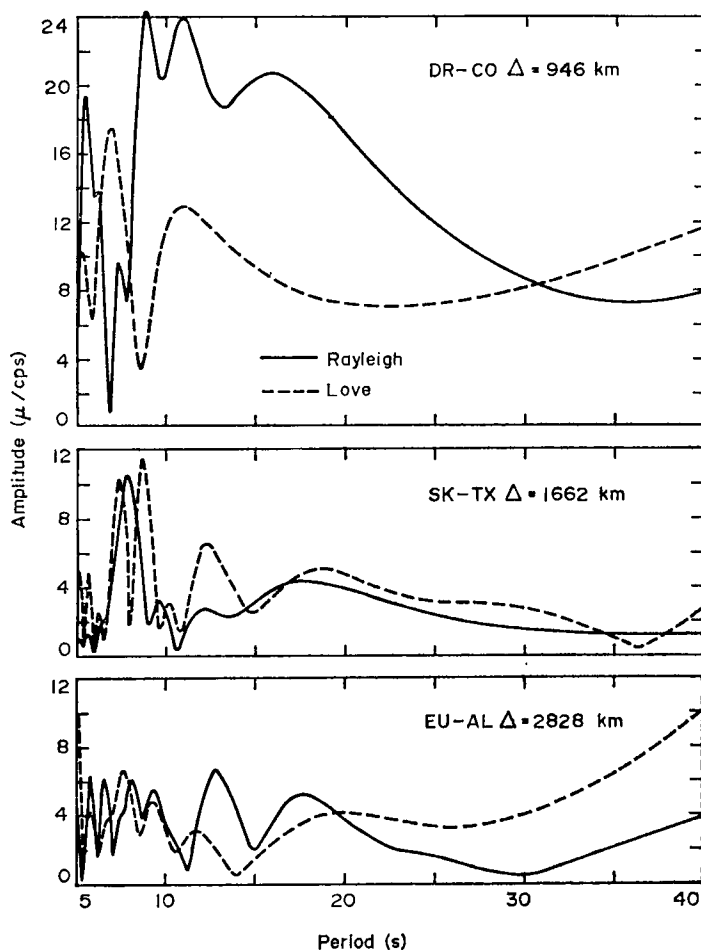


FIG. 7. Surface wave spectra at three distances for SHOAL. The points of observation are at approximately the same azimuth from the source. The Love and Rayleigh wave excitation are of roughly the same order, although at the nearest (and most reliable) station the Rayleigh wave excitation is generally greater over the reliable period range.

the ratio, the data appear to fit a linear dependence on frequency quite well. We will consider theoretical predictions of the relative Love wave excitation for explosion and earthquake models in a later study, with the objective of evaluating these predictions for various model types.

Since the power at the long-period end of the Love wave spectrum for the SHOAL explosion was low and probably significantly contaminated by noise, we have plotted in Fig. 9 the spectral ratios for the BILBY-FALLON pair (since BILBY has reasonably high power in the 20- to 40-s period range). There is a reasonably close fit to a $1/T$ dependence at the long-period end of the spectrum.

Taken together, then, these spectral ratios for Love waves from the explosions relative to the FALLON earthquake appear to follow a dependence which is roughly proportional to frequency where the observations are reliable. A possible explanation of this dependence is that the source dimension of the earthquake is significantly larger than that of the explosion.

Differences in spectral behaviour of Love and Rayleigh excitation can be brought out more clearly by studying the frequency-by-frequency ratio of the two surface wave types, which we denote as L/R spectra. First we consider the question whether the L/R ratio for earthquakes remains large compared to that for explosions as the period increases, and whether the difference in the L/R excitation for the different sources in this energy range can be distinguished at large distances.

In order to answer these questions we now consider the L/R spectra at stations along a nearly constant azimuth toward the east. This selection of azimuth does not maximize the difference between L/R for the earthquake compared to the explosions, as can be seen from comparing Figs 15, 17 and 20, but it is representative of the average difference likely to be seen over a distribution of stations rather than the extreme difference.

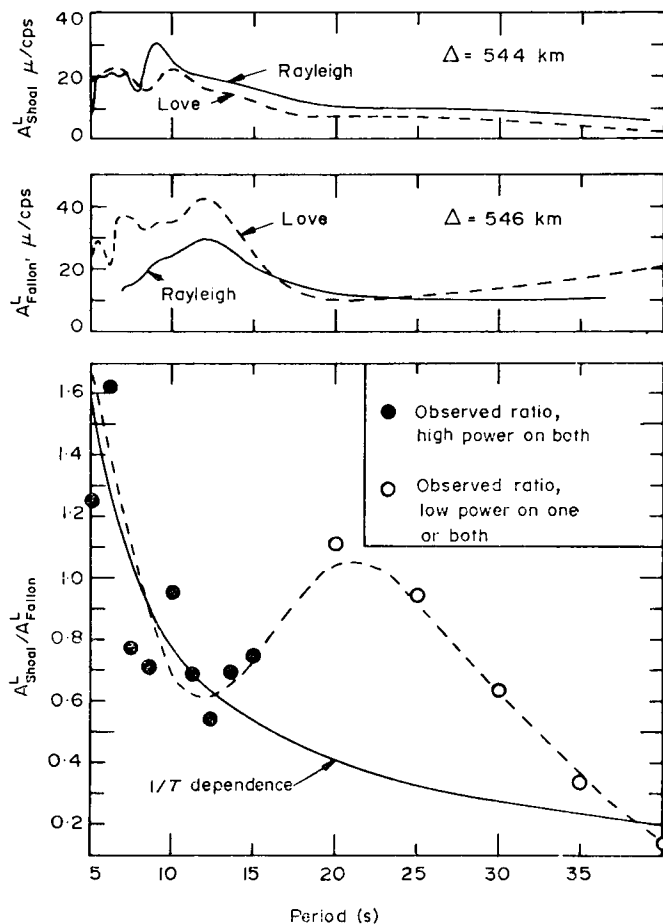


FIG. 8. Love wave spectra and spectral ratios for the SHOAL and FALLON events. The upper two graphs show the Love wave spectra for the individual events with the Rayleigh wave spectra given for comparison. Both spectra are individually normalized to unity at the maximum power point and the resulting normalized ratio of SHOAL to FALLON Love wave spectral density is plotted. The sampled spectral ratio is shown by the data points; the dotted curve is a smoothed fit to these sample points, and the solid curve is a $1/T$ curve for comparison.

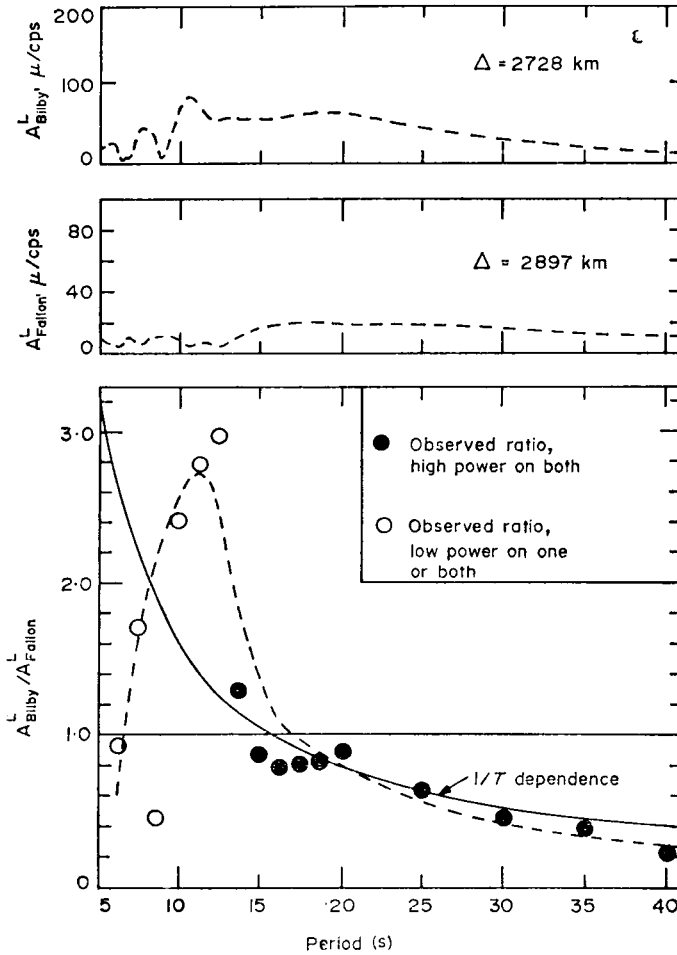


FIG. 9. Love wave spectra and spectral ratios for BILBY and FALLON. The upper two graphs show the Love wave spectra for the two events and the lower graph the normalized spectral ratio as described in Fig. 8.

Fig. 10 shows the L/R spectra at relatively close range for the three events studied. It is clear that the closely related SHOAL–FALLON pair behave very differently, since the L/R spectra for SHOAL remains rather flat and somewhat less than unity while that of FALLON is nearly 3.0 at the 10-s limit, increasing with increasing period, and approximately an order of magnitude larger at 30-s period. Generally speaking, the L/R ratio for BILBY is similar to that for SHOAL, although on the average it is somewhat larger in this period range. Thus over the frequency range where the observations are reliable, the L/R ratio for the earthquake is much larger than for the explosions, and increases with increasing period.

Fig. 11 shows the L/R spectra for the events at an intermediate teleseismic range, at approximately the same azimuths as those in Fig. 10. We note that roughly the same relationship between the events again holds. In this case, however, the spectral amplitudes for BILBY appear on average to be lower than for SHOAL. However, we do note that the distinction between the earthquake and the explosions in terms of L/R ratio at the short-period end of the spectral range has been lost. This

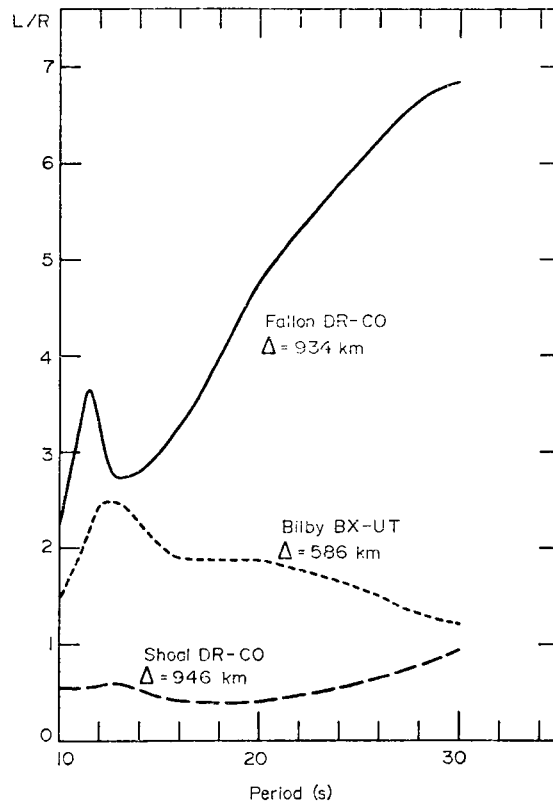


FIG. 10. The variation of L/R with period for the BILBY and SHOAL explosions and the FALLON earthquake, in the distance range near 800 km. L/R for the earthquake is larger than 2.0 and increases with increasing period. This difference in behaviour is a consequence of the much larger source dimension associated with the earthquake.

is probably due to the effects of structure, e.g. scattering from lateral variations. We also note that several maxima and minima occur in these spectra, whereas at closer distances the spectra were more regular; again, we consider this to be associated with structural irregularities. This emphasizes the danger involved in isolating a spectral peak (or a minimum in the spectrum of the vertical component of the Rayleigh wave) and associating it with a source depth effect. Harkrider (1970) considers in detail the question of the effect of source depth on the L/R spectral ratio, using the FALLON earthquake as an example.

Fig. 12 shows the surface wave spectra at a distance of nearly 3000 km from the sources. We note that the spectrum from FALLON has an L/R ratio which increases dramatically with period and actually extends to a value considerably larger than 20.0 at the longest period of the observed range. However, since the power at the extreme end of the range was low for FALLON, we do not consider the data beyond about 20- to 25-s period to be reliable. Nevertheless the spectrum maintains a much higher value than the explosions over a considerable period range. We also note that the SHOAL spectrum has a large peak near 30-s period, although the power was extremely low at this distance and period, and considering the noise levels and the effects of structure on such a spectral ratio we conclude that this peak may very well be spurious.

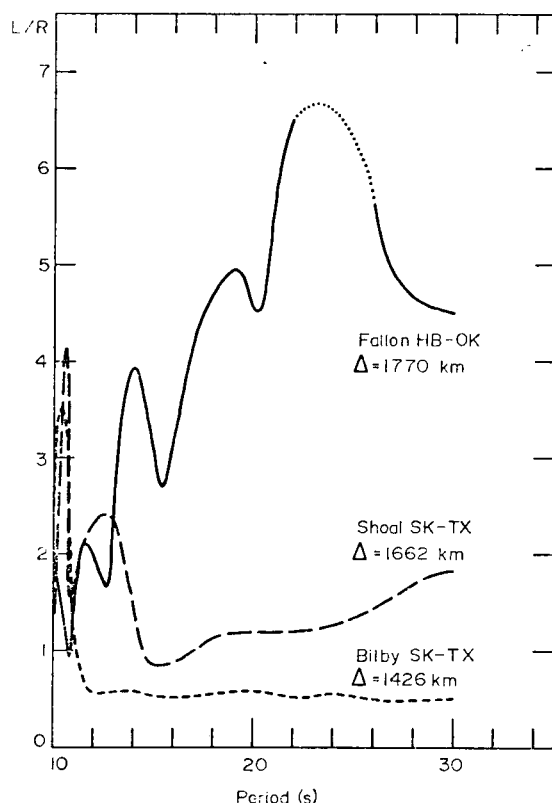


FIG. 11. The variation of L/R ratio versus period for the BILBY and SHOAL explosions and the FALLON earthquake, in the distance range near 1600 km. L/R for the earthquake is again considerably larger than that for the explosions and increases with increasing period at this larger distance range, as expected. Note, however, that the details in the variation of L/R versus period, i.e. local maxima and minima, are considerably different than in Fig. 10 and that the separation in the L/R is obscured at the short period end of the range.

These last three figures show that over a period range from about 10 to 35 s the L/R ratio is larger for this earthquake than for the explosions. It is clear that the spectral ratio of Love waves from the explosions relative to the earthquake shows that the long-period excitation for the anomalous explosion field has a fundamentally different frequency dependence within the range of observation (10- to 35-s period): the anomalous explosion field has a frequency dependence resembling ω^{m+1} (where m is some small positive integer) while the earthquake spectrum has a dependence like ω^m in this range. This implies that the source of the anomalous explosion field is quite different from the comparable earthquake, and we conclude that if the origin is tectonic it is associated with a region of relatively small dimension. This suggests that these effects are due to stress relaxation around the shatter zone.

Further, the spectral ratio of Love to Rayleigh waves generated by the sources studied here show that the earthquake (m_b 4.4) excited Love waves much more efficiently than did the explosions, and the difference in excitation increases with increasing period. We conclude that this difference might be useful in discrimination between the two sources types even for relatively low magnitudes, e.g. near m_b 4.4.

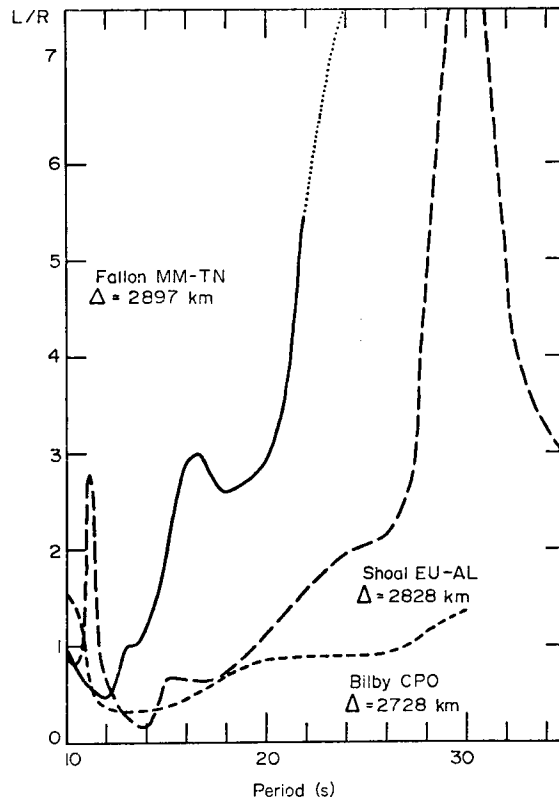


FIG. 12. The variation of L/R versus period for the BILBY and SHOAL explosions and the FALLON earthquake, in the distance range near 2800 km. At large distances the L/R separation between the earthquake and the explosions is maintained at long periods. The peak in the spectral ratio for SHOAL at 30 s is probably due to a path effect.

This observation also implies that the process of tectonic release was different for the explosions and the earthquake (which was of comparable body wave magnitude). This, in turn, suggests that the tectonic effects associated with the explosions are due to stress relaxation around the explosion-generated failure zone.

Surface wave radiation patterns and deduction of the equivalent multipole source

Concepts

An important concept underlying the theoretical framework of this research is that the elastodynamic field radiated outside the region containing the source can be represented in the frequency domain by a superposition of multipole contributions. This fact, familiar in the analogous cases of potential theory and electrodynamics, was formulated by Archambeau (1968) for a radiated elastic field. The implication is that we can represent the source of the radiated field as an equivalent point source located anywhere inside the actual region of energy release and adjust the multipole coefficients so that the observed field outside the source region is identical to that caused by the true source. Since the component multipoles are individually equivalent to particular superpositions of point forces, we can if we wish speak of force couples, double couples, etc., instead of multipoles, quadrupoles, and so forth. In the present

study we discuss the equivalent point sources for either the explosions or the earthquakes in terms both of the appropriate multipoles and their point force equivalents, depending on which designation is more familiar and useful in the particular context.

Since we deal in detail with monopole and quadrupole fields in this study, it is convenient to introduce parameters related to their force equivalents. For the double couple (the quadrupole equivalent) we define a plane along which one of the couples is oriented, the other couple being oriented perpendicular to it. Fig. 13 shows such a plane with its orientation in space specified by the unit vectors shown. For an earthquake this plane corresponds to the fault plane, which is simply a limiting form of the surface enclosing the region of failure. If the width of this region is small relative to its other dimensions, there is little geometrical distinction between the envelope surface and the fault plane shown in Fig. 13.

As is customary, the orientation of the fault plane is described by a strike angle measured from north and a dip angle measured from the normal to the strike direction, as shown. A point of observation (O) is specified by an azimuth angle θ measured from the strike direction, and an epicentral distance r measured from the point of initiation of the rupture; this latter point is shown in Fig. 13 as the origin of co-ordinates. If the fault plane or the actual rupture surface terminates at some depth h below the Earth's surface, the depth is measured in the direction of axis x_3 in Fig. 13, normal to the surface of the Earth.

We define $t^{(0)}$ in Fig. 13 as the traction vector at a distance $-\varepsilon/2$ just behind the fault plane when the fault plane is viewed from the direction defined by \hat{n} . When the

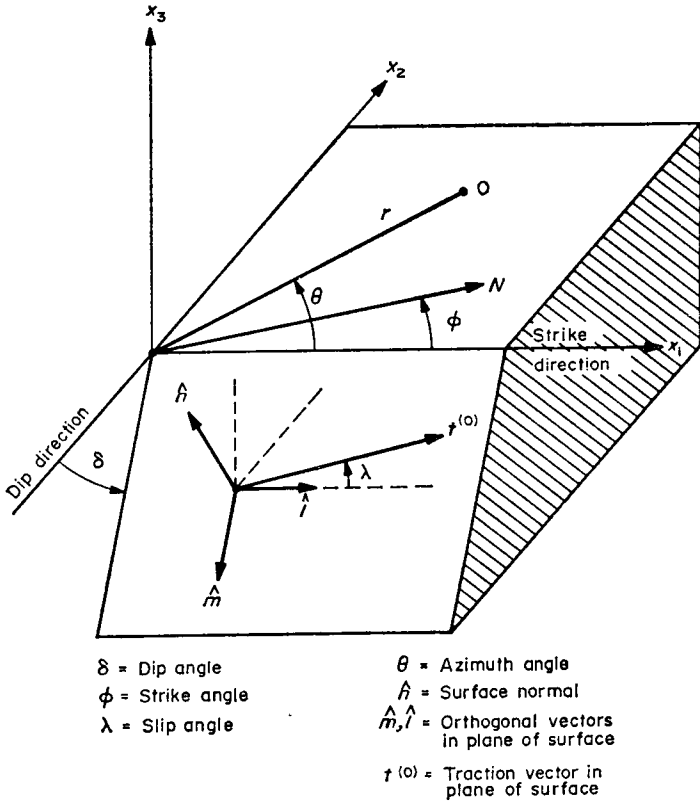


FIG. 13. Fault (or traction) plane geometry. The point (O) is an arbitrary point of observation, while the vector N is in the direction of geographic North.

fault plane is approached from the $-\hat{n}$ direction there is an equal and opposite traction $-t^{(0)}$ at a point at distance $+e/2$ just in front of the plane. This configuration of tractions defines one of the force couples for the equivalent source; its orientation in the plane will be described by the slip angle, which is simply the angle λ defined with reference to $-t^{(0)}$ as shown in Fig. 13. For the full quadrupole equivalent we require an equal and opposite couple whose orientation is perpendicular to the plane shown in Fig. 13 such that the net torque at the point P is zero. This particular configuration is required by the equilibrium equations, since for a relaxation process no net torques can be maintained. The origin of the second couple is the Poisson effect which occurs during relaxation.

For an earthquake the definition of the fault plane and the system of couples just described is intuitively appealing and reasonably straightforward (although from a purely intuitive approach only a single couple might appear to be required at first sight; this fact has contributed to the well-documented disagreement among seismologists as to whether a single or double-couple source is required). For stress relaxation associated with a 'spherical' shatter zone, however, the same equivalent double-couple point source applies, but of course the physical identification of a 'fault plane' is no longer obvious. Even so, we will define a plane through the source and its associated orientation parameters for this problem as well. In this case the plane and the couple orientation are related to the orientation of the prestress field.

This approach allows us to make direct use of Ben-Menahem & Harkrider's (1964) point source results to describe the quadrupole field from an earthquake and from an explosion in a stressed medium. Since we are primarily interested in theoretical fits to the azimuthal dependence of the radiation fields, we need only calculate the variation of a single function $\chi(\theta)$, which gives the radiation patterns for either Love or Rayleigh waves from a double-couple point source at a depth h in a plane-layered Earth model. In particular, Ben-Menahem & Harkrider (1964, equation 25) give:

$$\chi(\theta) = d_0 + i(d_1 \sin \theta + d_2 \cos \theta) + d_3 \sin 2\theta + d_4 \cos 2\theta$$

where for Rayleigh waves the coefficients are:

$$\begin{aligned} d_0 &= \frac{1}{2}B(h) \sin \lambda \sin 2\delta \\ d_1 &= -C(h) \sin \lambda \cos 2\delta \\ d_2 &= -C(h) \cos \lambda \cos \delta \\ d_3 &= A(h) \cos \lambda \sin \delta \\ d_4 &= -\frac{1}{2}A(h) \sin \lambda \sin 2\delta \end{aligned}$$

and for Love waves the coefficients are:

$$\begin{aligned} d_0 &= 0 \\ d_1 &= G(h) \cos \lambda \cos \delta \\ d_2 &= -G(h) \sin \lambda \cos 2\delta \\ d_3 &= \frac{1}{2} \sin \lambda \sin 2\delta \\ d_4 &= \cos \lambda \sin \delta. \end{aligned}$$

The functions $A(h)$, $B(h)$, $C(h)$, and $G(h)$ depend on the equivalent point source depth and on the details of the Earth model chosen. They are given explicitly by Ben-Menahem & Harkrider (1964, equations (26)–(36)), but since they are quite lengthy they will not be reproduced here. In this study we vary λ , δ , ϕ , and h to fit our observations, using a fixed average crust–upper mantle model appropriate to the

western United States. Without detailed path corrections we expect to see scatter in the observations about any fit, which of course limits to some extent our conclusions. However, with a good average structural model we can expect to be able to resolve and identify all but the more subtle variations in radiation patterns. We use model 35CM2 of Alexander (1963) for the structure near BILBY, and for SHOAL and FALLON we use the structure described by Toksöz, Harkrider & Ben-Menahem (1965), which is a modification of Eaton's (1963) model of the structure between San Francisco and Eureka, Nevada.

As for the monopole field from the explosion, we merely note here that it has the form:

$$\psi^{(2)}(r, \omega) = A_{00}{}^{\alpha}(\omega) h_0^{(2)}(k_{\alpha} r) \quad \alpha = 1, 2, 3, 4$$

where $h_0^{(2)}(k_{\alpha} r)$ is the Hankel function of the second kind, $k_{\alpha} = \omega/v_{\alpha}$, v_{α} is the shear velocity when $\alpha = 1, 2$ or 3 and the compressional velocity when $\alpha = 4$, and

$$A_{00}{}^{\alpha}(\omega) = [0, 0, 0, G(\omega)]^T.$$

The solution potentials $\psi^{(2)}$ are any one of the radiation vector components ($\alpha = 1, 2$ or 3) or the dilatation potential ($\alpha = 4$). The function $G(\omega)$ depends on the radius of the elastic-plastic boundary and on the effective dynamic pressure at this radius. Archambeau (1972) describes these functions and various ways of determining them. It is clear, however, that we can use a point source model and employ Ben-Menahem & Harkrider's results for a point pressure source without being directly concerned with the details of the function $G(\omega)$.

Our procedure in dealing with the explosion is to superpose point pressure and point double-couple sources and to scale the double-couple component by a factor F (see Toksöz *et al.* 1965); for observations of the radiation pattern at a given frequency we can adjust this factor F along with the other parameters of the double couple in order to obtain a theoretical fit to the observed radiation pattern.

Observed and theoretical radiation patterns

We now consider the surface wave radiation patterns associated with the two explosions and the single earthquake studied, and discuss the point-source models implied by the data.

Fig. 14 shows Love and Rayleigh wave patterns for the BILBY explosion at two frequencies which span the bandwidth of greatest signal power. We note that the stations closest to the source area give an adequate azimuthal coverage for our purposes, although more stations to the west would have been desirable. It is reasonably clear that variations in crust and upper mantle structure strongly perturb the radiation patterns; in particular, the stations in the eastern United States show quite large amplitudes which consequently cause distortions in the contours of the pattern. It appears that eastward-propagating surface wave energy, once across the Rocky Mountains, suffers little attenuation from there onward, and also that the observed surface wave amplitudes can actually be greater in the east than at stations in the western tectonic provinces which are much closer to the source. This can be explained in part by the fact that the crust in the eastern United States has intrinsically higher wave velocities in the intermediate and deep layers than does the crust in the Basin and Range Province (see, e.g. Archambeau, Flinn & Lambert 1969), and also the top of the upper mantle has higher velocity in the east than in the west. This results in a concentration of surface wave energy nearer the surface in the period range observed here (5 to 40 s) and hence higher amplitudes at the surface, even though the total wave energy is less.

The patterns in Fig. 14 for both Love and Rayleigh waves can be approximated by superposed quadrupole-monopole sources with both equivalent point sources

It is also significant that the same combination of monopole and quadrupole sources fits both the Love and Rayleigh waves. Further, we found very large changes in observed amplitudes of the radiation patterns between two frequencies where the shape of the pattern remains essentially invariant. In addition, over the entire range from approximately 10 s to 25 s the shape of the pattern did not vary significantly from that shown, although toward the ends of this range the observed power was low and the pattern resolution became poor. This shape invariance supports the idea that the physical mechanism associated with the double-couple source is not only physically located in the near vicinity of the explosion, but that the spectrum

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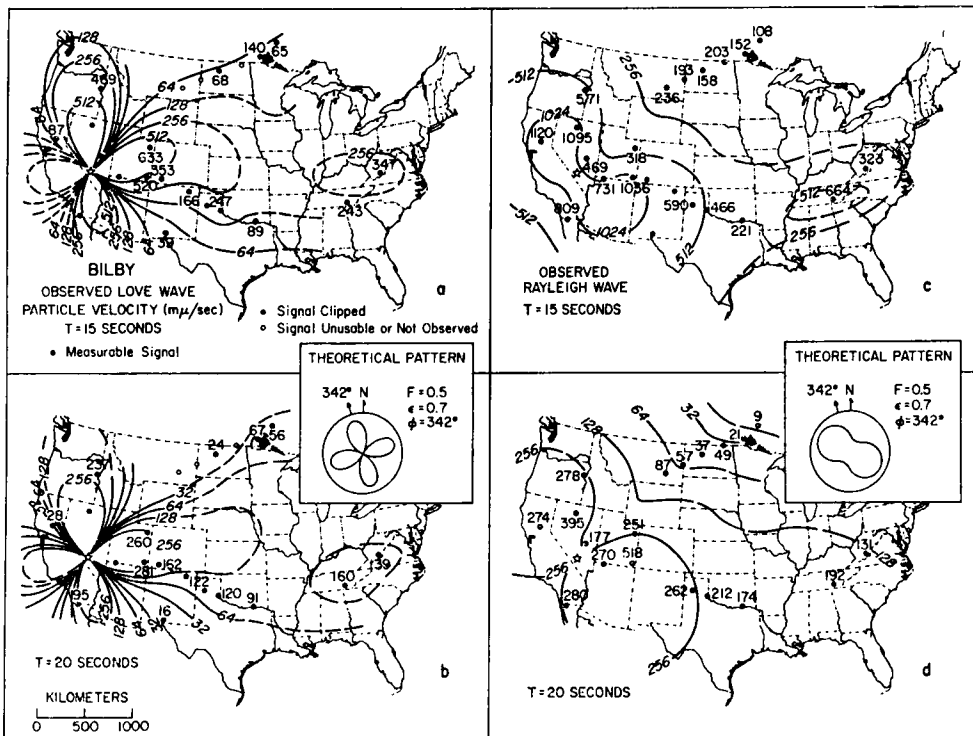


FIG. 14. Radiation patterns of Love and Rayleigh waves from BILBY at periods of 15 and 20 s. The insets show the theoretical pattern shapes obtained as a fit to the observations, using superposed monopole and quadrupole point sources with fixed relative excitation of quadrupole to monopole of $F = 0.5$, with quadrupole ‘strike’ $\phi = 342^\circ$. The point source equivalents are the same for both Love and Rayleigh waves. The factor $\varepsilon = 0.7$ is the particle orbit ellipticity factor for the Rayleigh waves, which depends on the structure used in the theoretical calculations.

Table 2

Source parameters for best fit to surface wave radiation patterns

	BILBY	SHOAL	Fallon earthquake
Equivalent fault type (double couple)	Right lateral	Right lateral	Right lateral
Strike	N 342° E	N 353° E	N 10° E
Dip	90°	90°	82° E
Slip angle	0	0	16°
<i>F</i> factor	0.5	0.58	—

produced by this mechanism is similar in shape to that of the explosion spectrum (as a function of frequency over the range observed here). Indeed, the scaling factor $F = 0.5$ for the double couple is independent of frequency over the observed range; thus $G(\omega)$ is such that the actual source monopole spectrum is similar to the quadrupole spectrum predicted for radiation due to relaxation around the shock-created shatter zone. The magnitude of this excitation factor is also of the order expected for relaxation.

The amplitude and energy spectrum produced by this double-couple source component from BILBY has been studied by Archambeau & Sammis (1970), who considered the hypothesis that this contribution to the field is actually due to tectonic prestress relaxation around the shock-induced shatter zone. They found that a fit could be achieved for a homogeneous shear prestress of 70 bars and a shatter zone of roughly 400-m radius, which are physically reasonable values. Thus we may tentatively conclude that our observations from BILBY support the hypothesis of this form of tectonic release. We do not see the change in pattern shape that large-scale faulting would imply, and while we cannot definitely rule out a triggering effect there is little evidence to support it. However, Aki *et al.* (1969) have drawn the opposite conclusion from observations of the BENHAM explosion and its aftershocks.

As to the fundamental question of whether tectonic effects are responsible for the double-couple component, we note that at this point the strike and dip of the 'couple plane' ($\phi = 342^\circ$, $\delta = 90^\circ$) are consistent with the orientation of tectonic features in the vicinity of the explosion site. This simply indicates that the average stress field in the region is oriented so as to produce a double-couple field in agreement with the observations for either fault triggering or shatter-zone relaxation effects. Therefore the tectonic hypothesis is at the very least consistent with our present observations. Furthermore, while our fit to the amplitude pattern suggests that the origin of the double-couple source is in the near vicinity of the explosion (within a few tens of kilometres at most), observations of the Love wave group velocity require that the double couple be very close to the explosion site because the observed group velocities must be compatible with the reasonably well-known crustal structure along the propagation paths. Hence while one might argue from the observations of Rayleigh waves along that the radiation patterns might be accounted for by amplitude fluctuations caused by local structural variations at the individual stations, it is impossible under such a hypothesis to explain both the Love and Rayleigh wave group velocity observations, which are after all consistent with our prior knowledge of source-to-station velocity structure within the Basin and Range Province. Therefore we can conclude that only a double source at the explosion location can explain all our observations.

The theoretical patterns shown in Fig. 14 provide a rather qualitative way of fitting the observations; that is, we have tried to fit by adjusting the general shapes of the contours to the observed amplitudes. A more quantitative approach is achieved by the method illustrated in Fig. 15 where we simultaneously consider the Love and Rayleigh wave amplitude patterns (the vertical component amplitude of the Rayleigh waves) by fitting their L/R ratio as a function of frequency. We now consider a reasonable frequency sampling of such L/R patterns and fit them with a fixed combination of monopole and quadrupole parameters. The parameters are the same as for the patterns shown in Fig. 14 and listed in Table 2, of course. The L/R fit is seen to be quite good. All the source parameters listed remained nearly constant over the period range 10–35 s. The character of the L/R ratio in the previous section verifies this fact. Thus we can conclude that the mechanism producing the double-couple component for BILBY is probably tectonic stress relaxation near the roughly spherical shatter zone.

The SHOAL explosion was considerably smaller than BILBY (Table 1), but a double-couple component similar to that obtained for BILBY was observed. Fig. 16 shows the SHOAL radiation patterns, which are similar in shape to those observed from BILBY. The theoretical fit gave an F factor and double-couple source depth which are similar to those of BILBY, and the same interpretation can be made: the shape invariance of the patterns with frequency (over the period range 10–30 s in this case), the coincidence of the quadrupole and monopole source depths, the fact that the strike and dip of the equivalent 'fault' plane coincide with

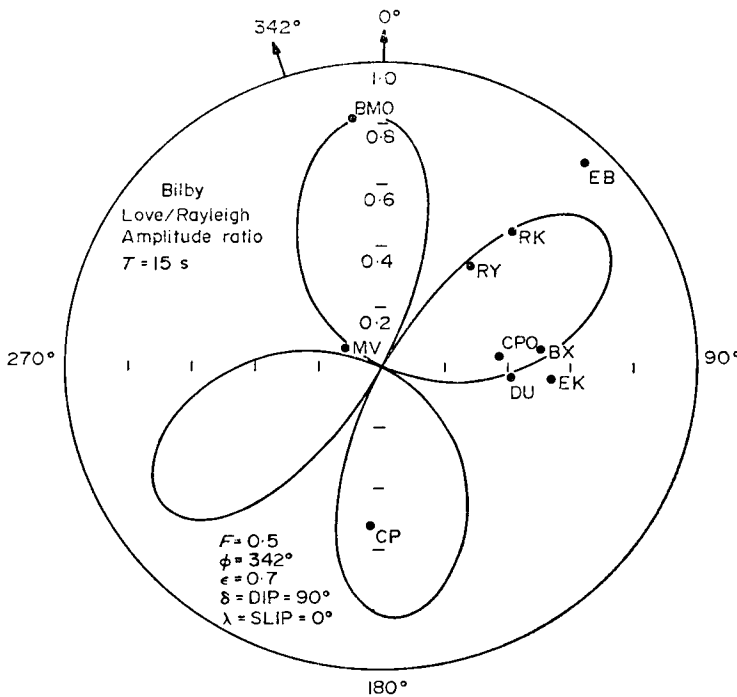


FIG. 15. The theoretical L/R for BILBY, at $T = 15$ s, as a function of azimuth using the source parameters of Fig. 14. The observed ratio at a number of stations with good signal-to-noise ratios for both Love and Rayleigh waves are shown at their appropriate azimuths. This also shows the nature of the L/R azimuth variation, and it is clear that a single equivalent source fits both Love and Rayleigh wave radiation for this event.

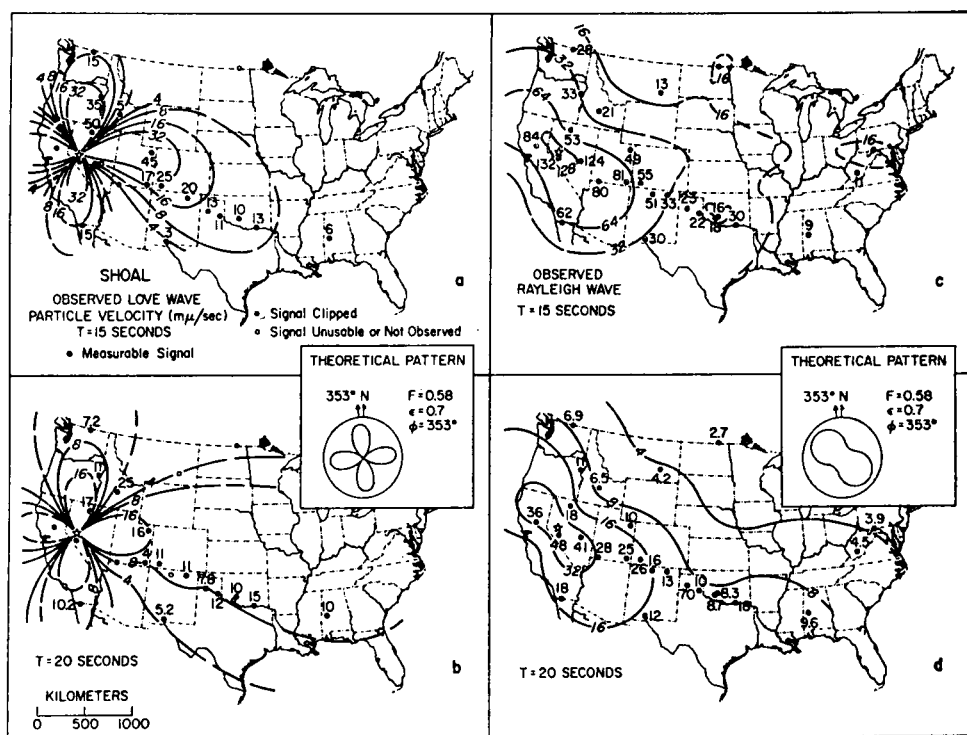


FIG. 16. Radiation patterns of Love and Rayleigh waves from SHOAL at periods of 15 and 20 s. The insets show the theoretical patterns obtained as a fit to the observations using a superposed monopole and quadrupole point source with fixed relative excitation of quadrupole to monopole of $F = 0.58$, with quadrupole 'strike' $\phi = 353^\circ$. The point source equivalents are the same for both Love and Rayleigh waves.

tectonic features of the area, and the moderate value of F as well as its independence of frequency: all these imply tectonic release due to stress relaxation near the explosive shatter zone. Further, the source parameters defining the double-couple component are nearly identical with those obtained for BILBY, which also implies a similar tectonic stress field in the two areas.

Fig. 17 shows the L/R pattern at a period of 15 s. The fit to the data is quite good considering the large variance to be expected in the ratio of two spectra, due, for example, to structural effects and to the presence of noise. The scatter from the theoretical fit is also expected to manifest itself in azimuthal displacement of the observed points of this plot, because of lateral variations in Earth structure. Such lateral variations in structure have not, of course, been taken into account in our theoretical calculations, but these effects are quite apparent in Fig. 16, and it is easy to see that in the vicinity of the epicentre the observed pattern fits the theoretical pattern quite well, while at greater distances the energy has been refracted and scattered by horizontal velocity gradients along the path so as to distort the basic symmetry observed near the source. We note that the effect of lateral variations in structure on the pattern shapes should be frequency dependent, and Fig. 16 illustrates this fact.

One of the major considerations of this study is the comparison of the radiation field of an earthquake to that of underground explosions. The epicentre of the

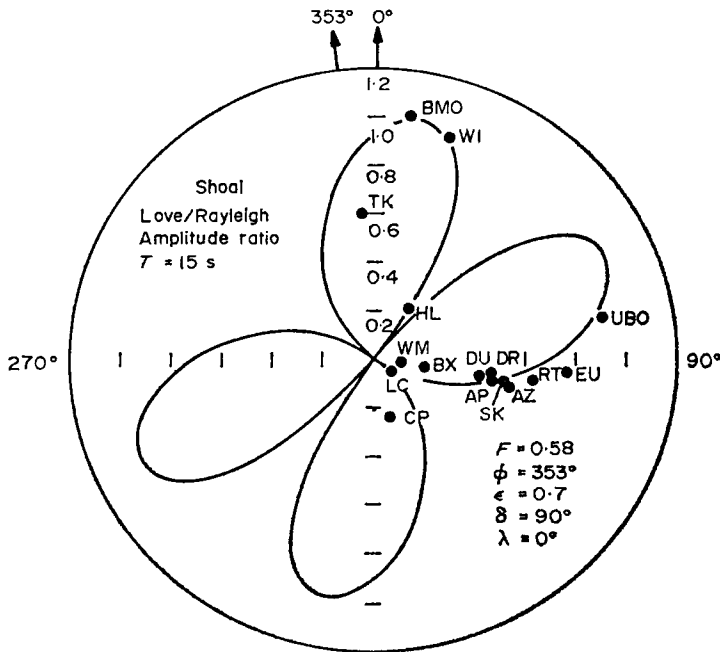


FIG. 17. The theoretical L/R ratio for SHOAL, at 15-s period, as a function of azimuth and using the source parameters of Fig. 16. Observations at various azimuths where signal-to-noise ratios were high are indicated and identified by abbreviated station symbols. This also shows the nature of the L/R azimuth variation (which is nearly identical to that for BILBY) and that a single equivalent source fits both Love and Rayleigh wave radiation for this event.

Fallon earthquake was very near the SHOAL explosion site, so the comparison with SHOAL is straightforward.

Fig. 18 shows the Love wave radiation patterns from the Fallon earthquake; the inset shows the double-couple equivalent which we consider to give a best fit to these observations. The same source equivalent was used to fit the Rayleigh wave patterns and the L/R data. The parameters for this source equivalent are to be compared to the double-couple parameters obtained from the SHOAL explosion. The most significant difference between the double-couple equivalents for the two sources is the difference in depth of the earthquake double couple. In view of the strong constraints placed on source depth by the radiation patterns, we are reasonably confident that an appreciable difference in depth does exist. We therefore believe that this is an example of what a triggered event at depth would contribute to the surface wave radiation from an explosion. We note that the earthquake has a significantly lower body wave magnitude than the explosion (Table 1) and hence is energetically of the same size and depth that have been hypothesized for triggered seismic events associated with explosions in the magnitude range of SHOAL and BILBY. We must immediately note, however, that beside the fact that an equivalent double couple at the surface (rather than one at significant depth) provides a best fit to the explosion data, it is also evident that the double couple for the earthquake has a much greater excitation in the 10- to 30-s period range than does that of the explosion. This is evident from comparison of the Love wave amplitudes for FALLON with those for SHOAL and is even clearly true for BILBY, which is more than an order of magnitude larger in energy than FALLON. Thus we would expect that if a triggered earthquake occurred along with the explosions it would have characteristics

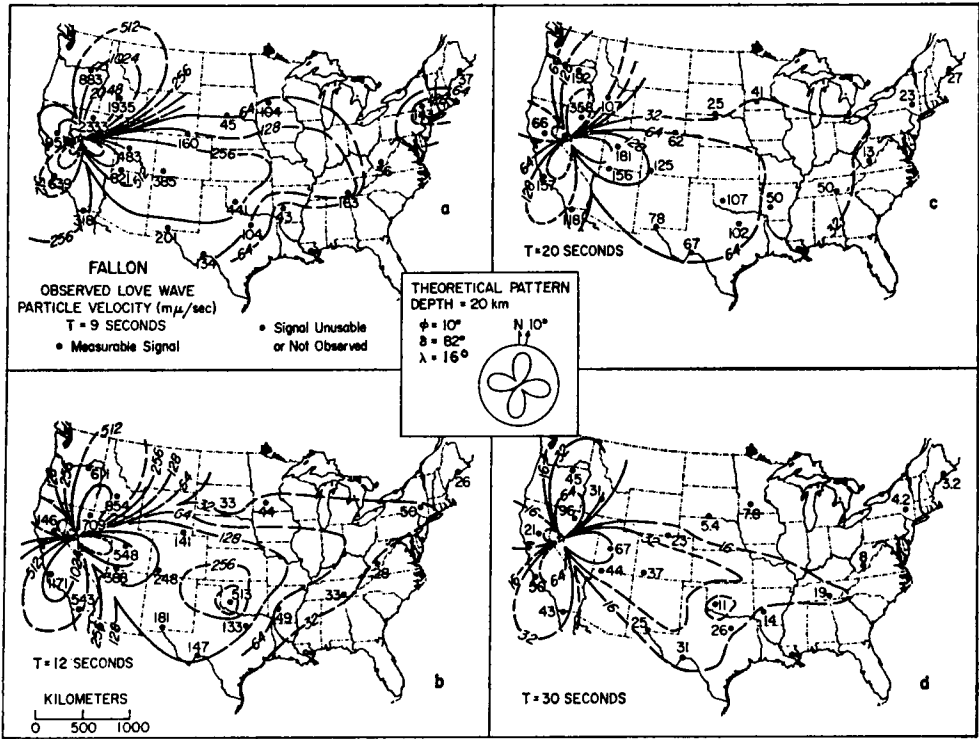


FIG. 18. Radiation patterns for Love waves from the FALLON earthquake at periods of 9, 12, 20 and 30 s. The inset shows the theoretical pattern shape obtained as a fit using a point quadrupole (double couple) located and oriented as indicated. The orientation of the quadrupole is close to that obtained for SHOAL, indicating that the stress field orientation was similar for both. The data and contours for the field at 9-s period show (a) asymmetries in the near-source pattern, indicating rupture propagation effects or perturbation in the pattern due to strong lateral variations in structure. These diminish with increasing period [(b), (c) and (d)], except for the point of observation in northern California; this anomaly may be due to the strong structural variation at the Sierra Nevada–Basin and Range boundary.

very similar to FALLON, especially of course for SHOAL. However, we see that the observed characteristics of the anomalous double-couple components associated with the explosions are very different from those of the earthquake, and hence we are again led to conclude, in agreement with Archambeau's source theory, that the probable mechanism is tectonic release associated with the highly symmetric fracture zone created by the explosive shock wave.

Another aspect of the comparison between the quadrupole components of SHOAL and FALLON is the similarity in the orientation of the equivalent double couples. We expect that if the origin of the Love waves for the explosion is tectonic stress relaxation, then the orientation of the double-couple equivalent for the explosion should be similar to that for the earthquake—provided, of course, that the prestress field is reasonably well behaved in such a way that averages taken over volumes of the order of kilometres in diameter do not vary much in this region. We observe from comparison of the parameters describing the double-couple equivalents for the explosion-earthquake pair, illustrated by the insets in Figs 16 and 18, respectively, that there is a strong correlation of the orientation of the double couples although there is a large difference in their relative magnitudes. This is consistent with the idea

that tectonic relaxation of a regional stress field was involved in both cases, and that the earthquake was much more efficient in this regard at low frequencies.

If we examine the radiation patterns shown in Fig. 18 in more detail we see that the theoretical quadrupole pattern is a rather rough approximation to the observations although a good first-order fit. There are at least two possible reasons: first, we might expect that rupture propagation effects would distort the patterns at wavelengths comparable to the rupture length (Archambeau & Minster 1972, in preparation); second, structural variations may cause perturbations in the patterns. Both effects appear to be present here. Note in particular the distortion of the pattern at 9-s period. The amplitudes on the northeast lobe of the pattern appear to be three to four times larger than those on any of the other lobes. This effect diminishes rapidly with increasing period. We consider this deviation from a pure quadrupole pattern to be predominantly due to rupture propagation, although we cannot definitely rule out structural focusing effects. Although the surface wave amplitudes were low at short periods for SHOAL, we did not see similar effects there. If either structural effects or fault triggering were significantly involved in SHOAL, manifestations such as pattern distortion should have been evident.

Structural inhomogeneities obviously are important, however. For example, the surface waves propagate efficiently east of the Rocky Mountains, and the lobes of the radiation pattern in the eastern part of the continent shift toward the south with increasing period, which implies that the wave velocity in the lower crust and upper mantle is higher in the north-east—or at least that such a variation is consistent with an observed refraction effect and agrees with the known structural variation in this part of the continent.

Fig. 19 shows the Rayleigh wave pattern from FALLON along with the theoretical pattern produced by the same quadrupole model used to fit the Love waves. Because of the orientation of the equivalent double couple, the pattern shape here changes with frequency. We observe a remarkable first-order agreement between the theoretical and observed patterns, particularly when the combined Love and Rayleigh wave data are considered. Again, there are strong perturbations in the patterns due to structure, particularly in the east. However, close to the source there appears to be evidence for rupture propagation in the distortion of the pattern, which results in larger amplitudes toward the north at short periods. Again a strong conclusion on this point is not possible, but at least the radiation patterns of both Love and Rayleigh waves show the effects that would be expected due to rupture propagation.

In the east the effects of lateral structural variations are different for the Rayleigh waves and Love waves in that we observe no similar rotation of the pattern from north toward south for the Rayleigh waves. However, the Rayleigh wave amplitudes are smaller, and noise may obscure the true behaviour of the pattern as a function of period.

A composite picture of the Love and Rayleigh wave radiation is provided by the fit to the Love to Rayleigh spectral ratio. Fig. 20 shows the L/R radiation pattern a 16 s, a period at which both types of surface waves have large amplitude. Fig. 21 shows the variation in the theoretical fit with changes in source depth. This variation suggests that the source depth is actually quite strongly constrained by the observations, so that to within a few kilometres we can be reasonably confident of the depth estimate of 20 km. Considering the combined effects of lateral structural variations and rupture propagation as perturbing influences, the simple quadrupole pattern shown gives a remarkably good fit to the data. The important point here is that the L/R ratio for FALLON is much larger than the L/R ratio for SHOAL. In the period range 10–35 s this is true at every azimuth with the exception of only those (singular) points along the nodal lines. Similar observations over a broader period range might be potentially useful in distinguishing earthquakes from underground explosions.

Discussion of possible ambiguities

We note that some of the less obvious difficulties inherent in fitting theoretical predictions to the observations arise from a lack of uniqueness; these are best illustrated by actual examples.

Since the azimuthal variation of the L/R ratio at a given frequency is an important variable, it is appropriate at this point to discuss the effect on the L/R radiation pattern of variations in the free parameters describing the source. For an explosion with an anomalous quadrupole or double-couple component, we have as variables the depth of the double couple and the strike, dip, and slip angles describing its orientation, as well as the F factor relating the amplitude of monopole excitation

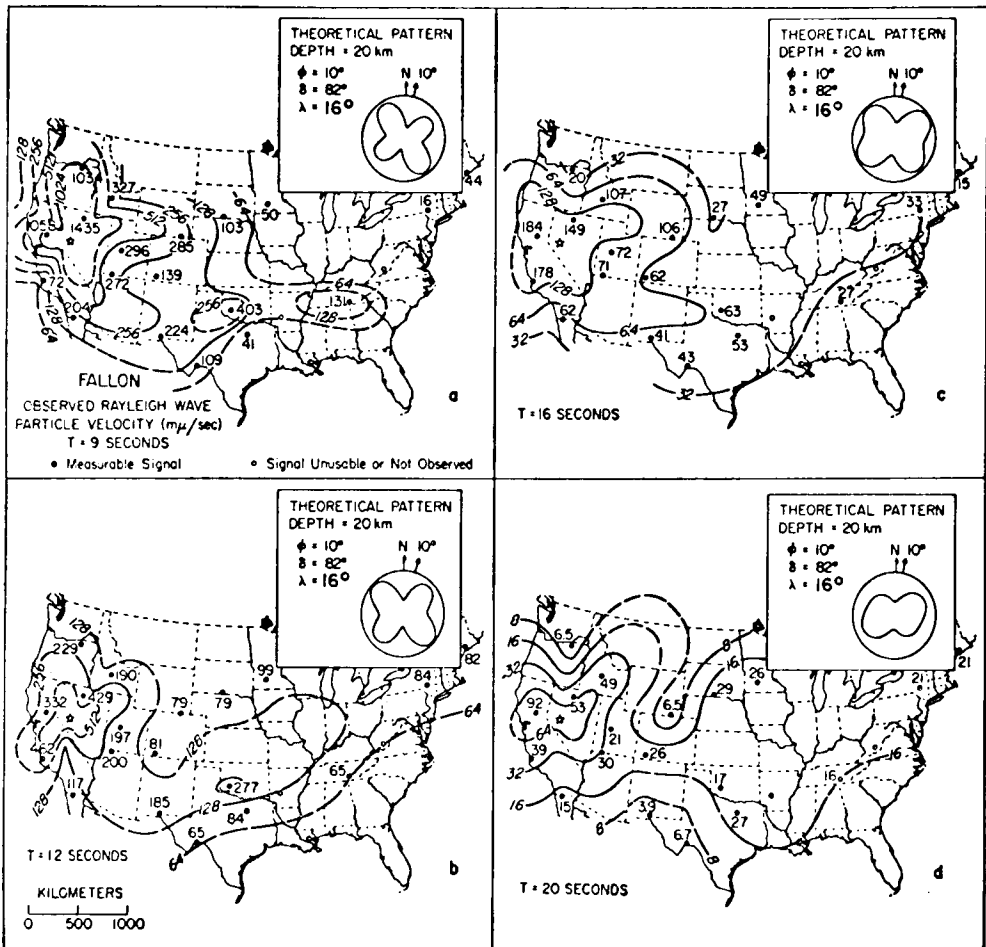


FIG. 19. Radiation patterns for Rayleigh waves from the FALLON earthquake at periods of 9, 12, 16 and 20 s. The insets show theoretical patterns from the same point quadrupole source used to obtain the theoretical fits to the Love wave radiation patterns in Fig. 18. The theoretical patterns for the Rayleigh waves change as a function of period, as opposed to the patterns for Love waves, probably due to the medium layering. This is a medium effect and should not be confused with pattern shape changes due to the intrinsic properties of the source itself. As for the Love waves, there appears to be evidence of rupture propagation effects in the asymmetry of the pattern at short periods ($T = 9$ s in particular).

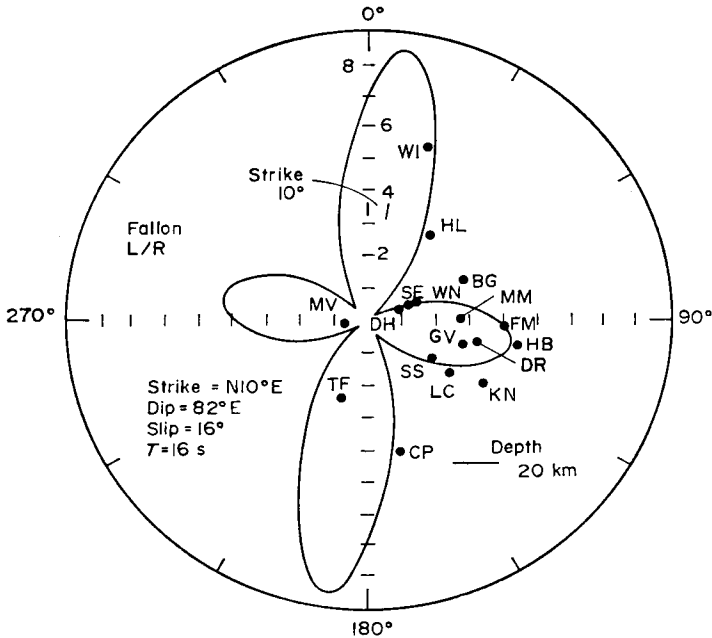


FIG. 20. The theoretical L/R ratio for FALLON at 16-s period, as a function of azimuth, using the source parameters obtained for the results shown in Figs 18 and 19. Observations at various azimuths where the signal-to-noise ratios were high are indicated and identified by abbreviated station symbols. This shows the nature of the L/R azimuth variation for an earthquake in the same environment as the comparable explosion SHOAL (see Fig. 17). The L/R ratio for this event is much larger than that for the explosion at all comparable azimuths, except along nodal lines.

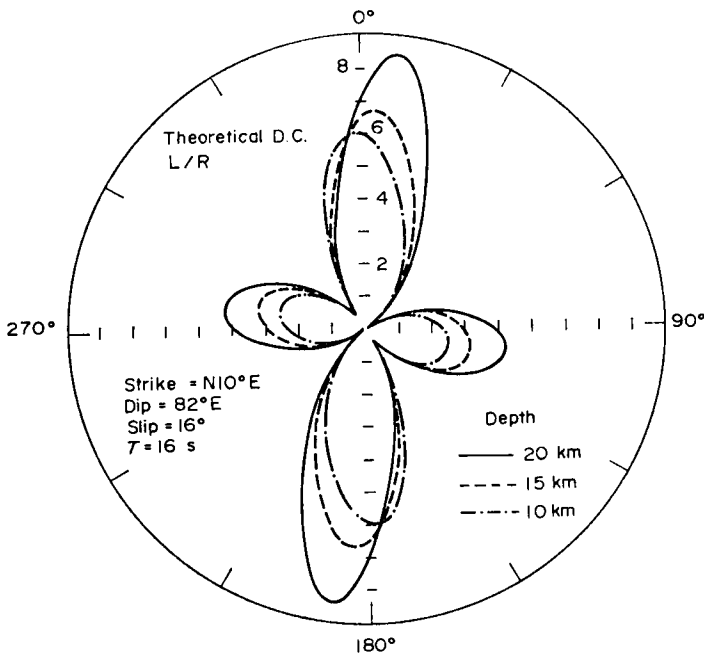


FIG. 21. Variation of the L/R ratio as a function of the equivalent double-couple depth for the FALLON earthquake.

relative to the quadrupole excitation. We note parenthetically that the depth of the equivalent double couple required to explain the observations could be diagnostic of the mechanism of the quadrupole field if it is significantly different from the known depth of the explosions: a much greater depth, for example, would suggest triggering of an earthquake, while a depth near that of the monopole equivalent might be caused either by triggering, relaxation due to the shatter zone itself, or by wave type conversion.

Many variations of combinations of these parameters can give rise to closely similar L/R patterns. For example, Fig. 22(a) and (b) show that the patterns for slip angles larger than 180° can be generated from those with λ less than 180° by reflection about the zero azimuth line. We have used this symmetry property in the presentation of some of our results: when we employ slip angles near 0° or 180° it is with the understanding that we may go from one to the other by simply reflecting the pattern about the zero-azimuth line. A similar variation in the pattern, involving slight azimuthal rotations and changes of magnitude, can be caused by changes in the

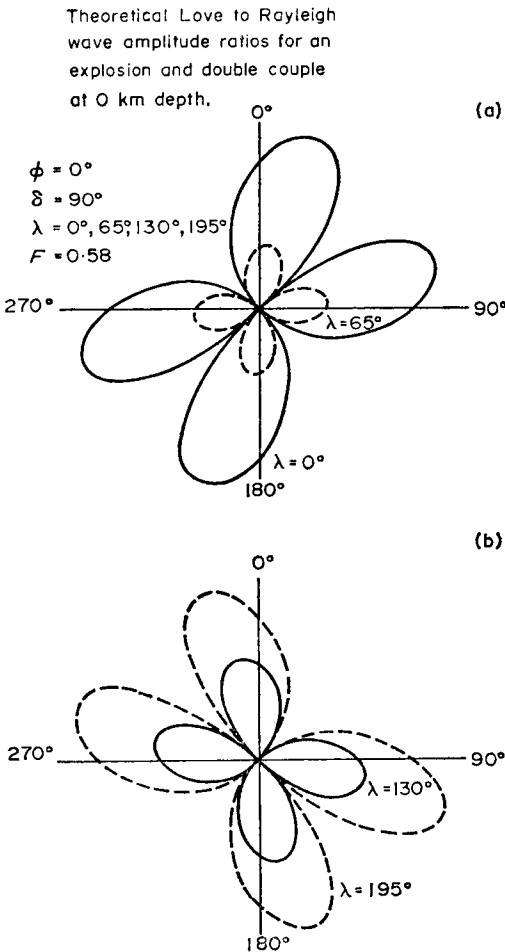


FIG. 22. Variation of the Love to Rayleigh (L/R) wave ratio as a function of λ , double-couple 'slip angle', for superposed monopole and quadrupole (double-couple) components. The relative excitation of the quadrupole to monopole component is fixed at $F = 0.58$ for all frequencies.

depth of the double-couple component. Fig. 23 shows the variation in pattern shape associated with a change in the depth of the quadrupole component, holding the depth of the monopole component fixed at zero. We see that the L/R ratio is not strongly dependent on the double-couple component depth at this frequency, and in addition, referring to Fig. 22(b), it is evident that decreasing the slip angle from 195° while keeping both source components fixed at zero depth could produce a result similar to that illustrated in Fig. 23. Consequently, different combinations of slip angle and double couple depth equivalent can result in nearly the same observed radiation pattern. A similar ambiguity exists in the combination of dip angle and the F factor for an explosion. Fig. 24 shows the change in the L/R pattern for varying dip angle, holding the other parameters fixed. Here the pattern lobes increase in magnitude with increasing dip, and essentially the same kind of variation occurs as F increases.

It is evident from Figs 22–25 that a lack of uniqueness exists involving the slip angle λ , the depth of the double-couple component, the dip, and the F factor. Thus we are confronted again with the fundamental lack of uniqueness which is characteristic of most geophysical problems.

In our treatment of the actual observations and the theoretical fit to the data, we therefore have worked in a period range in which the scatter of data is small, so that with reasonable justification we can make relatively fine distinctions between the fitted models. We also constrain our solutions to be in at least rough agreement with the known tectonic setting of the source area. We thus make use of the fact that something is known of the strikes and dips of the faults in the source region, and we have imposed a set of constraints on our allowable source models. Further, the ambiguities for the earthquake are not as serious as for the explosions, since we deal with only one type of equivalent source, and so we have used the fit for the double couple of the earthquake as a guide for possible solutions for the SHOAL explosion.

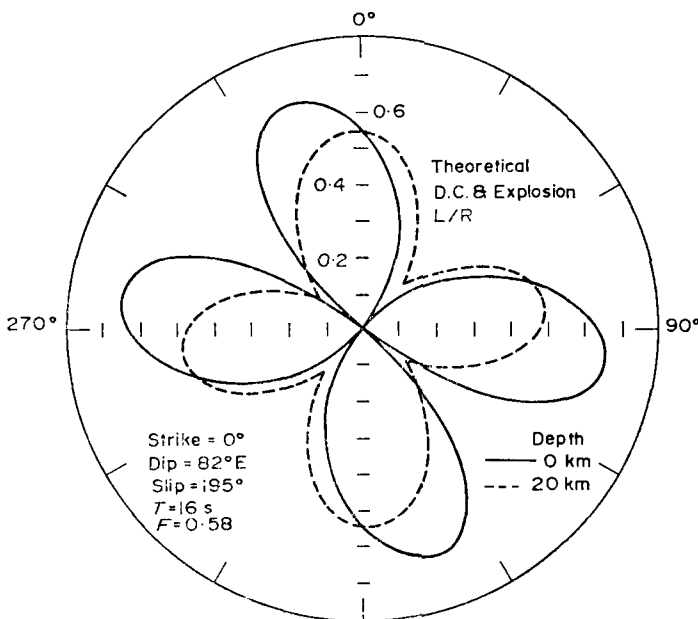


FIG. 23. Variation of the Love to Rayleigh wave ratio (L/R) as a function of the double-couple source component depth, holding the monopole component depth fixed at 0 km. All other source parameters are fixed at the values indicated.

Theoretical Love to Rayleigh
wave amplitude ratios for an
explosion and double couple
at 0 km depth.

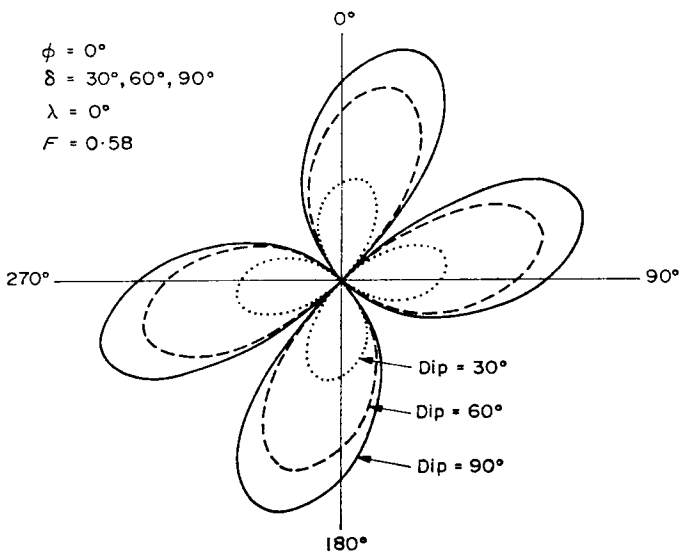


FIG. 24. Variation of the L/R ratio as a function of δ and the double couple 'dip angle' for superposed monopole and (double couple) quadrupole components. All other source parameters are fixed as indicated.

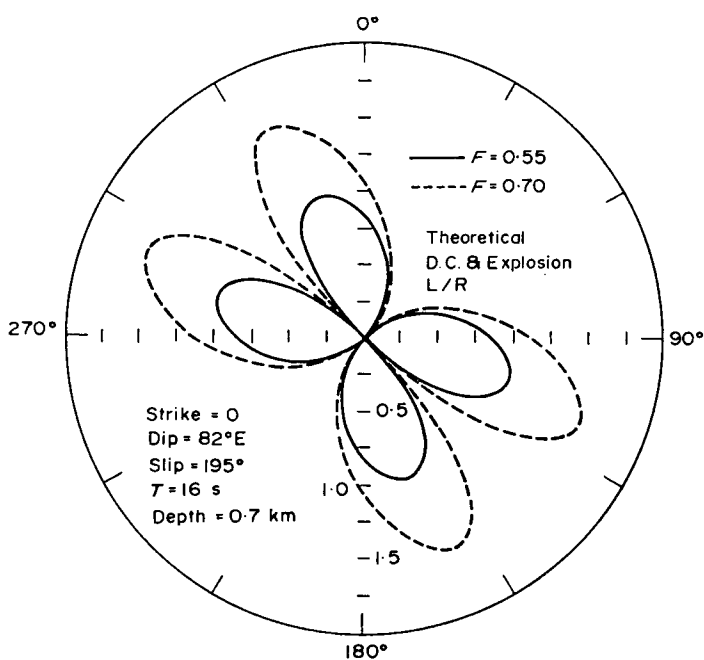


FIG. 25. Variation of the L/R pattern as a function of F , the relative excitation of the monopole and quadrupole source components. Both components are at the depth indicated, and all other parameters are fixed.

This presupposes tectonic release as the origin of the double-couple component, of course, and hence only serves to constrain permissible solutions of this type. Further, in this study our main argument for acceptance of the hypothesis of tectonic release (rather than conversion) is the quality of the fit to our observations. At the very least the observational data can be taken at face value, and we can assert that we have quantitatively determined the first two multipole contributions, regardless of their origin.

Conclusions

We draw the following conclusions from this study:

(1) The earthquake radiation field is to first order a quadrupole field in the spectral range where typical wavelengths of the radiated field are larger than the rupture dimensions. At shorter periods there are indications of higher-order multipole contributions produced by rupture propagation, both in the radiation patterns and the spectra. These results are in quantitative agreement with the theoretical predictions.

(2) The anomalous field from the explosion is purely quadrupole over a wide spectral range. Since the Rayleigh wave radiation patterns do not approach a quadrupole type at longer periods, and since the Love to Rayleigh excitation ratio is near unity, we conclude that the source spectrum for the anomalous field is similar in shape to that for the explosive monopole component of the total field. This is in agreement with theoretical predictions for stress relaxation around the shock-generated failure zone.

(3) The Fallon earthquake excited Love waves much more efficiently than did the explosions, with the excitation increasing with increasing period. We conclude that this difference could be useful in discrimination between the two source types, even for relatively low magnitudes, e.g. near m_b 4.4. We have not, of course, demonstrated that this difference exists for all earthquakes.

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References

- Aki, K., Reasenburt, P., De Fazio, T. & Tsai, Y. B., 1969. Near-field and far-field seismic evidence for triggering of an earthquake by the BENHAM explosion, *Bull. seism. Soc. Am.*, **59**, 2197-2208.
- Alexander, S. S., 1963. *Surface wave propagation in the western United States*, Ph. D. Thesis, California Institute of Technology, Pasadena, California.

- Archambeau, C. B., 1968. General theory of elastodynamic source fields, *Rev. Geophys.*, **6**, 241–288.
- Archambeau, C. B., 1972. The theory of stress wave radiation from explosions in prestressed media, *Geophys. J. R. astr. Soc.*, **29**, 329–366.
- Archambeau, C. B., Bradford, J. C., Broome, P. W., Dean, W. C., Flinn, E. A. & Sax, R. L., 1965. Data processing techniques for the detection and interpretation of teleseismic signals, *Proc. IEEE*, **53**, 1860–1884.
- Archambeau, C. B. & Flinn, E. A., 1965. Automated analysis of seismic radiation for source characteristics, *Proc. IEEE*, **53**, 1876–1884.
- Archambeau, C. B., Flinn, E. A. & Lambert, D. G., 1969. Fine structure of the upper mantle, *J. geophys. Res.*, **74**, 5825–5866.
- Archambeau, C. B. & Sammis, C., 1970. Seismic radiation from explosions in prestressed media and the measurement of tectonic stress in the Earth, *Rev. Geophys.*, **8**, 473–499.
- Ben-Menahem, A. & Harkrider, D. G., 1964. Radiation patterns of seismic surface waves from buried dipolar point sources in a flat stratified earth, *J. geophys. Res.*, **69**, 2605–2620.
- Eaton, J. P., 1963. Crustal structure from San Francisco, California, to Eureka, Nevada from seismic refraction measurements, *J. geophys. Res.*, **68**, 5789–5806.
- Harkrider, D. G., 1964. Surface waves in multilayered elastic media: I. Rayleigh and Love waves from buried sources in a multilayered elastic half-space, *Bull. seism. Soc. Am.*, **54**, 627–679.
- Harkrider, D. G., 1970. Surface waves in multilayered elastic media: Part II. Higher mode spectra and spectral ratios from point sources in plane-layered earth models, *Bull. seism. Soc. Am.*, **60**, 1937–1987.
- Lambert, D. G., Flinn, E. A. & Archambeau, C. B., 1972. A comparative study of the elastic wave radiation from earthquakes and underground explosions, *Seismic Data Laboratory Report No. 284*, Teledyne Geotech, Alexandria, Virginia (available from the Federal Clearinghouse for Scientific and Technical Information, Springfield, Virginia as document number AD 737-125).
- Rader, C. M. & Gold, B., 1969. *Digital signal processing*, McGraw-Hill Book Co., New York.
- Toksöz, M. N., Harkrider, D. G. & Ben-Menahem, A., 1965. Determination of source parameters by amplitude equalization of seismic surface waves: Part 2. Release of tectonic strain by underground nuclear explosions and mechanisms of earthquakes, *J. geophys. Res.*, **70**, 907–922.